

# Investigation of Lateral Strains Involved in Ultrasonic Pulse Velocity Test by Using Finite Element Methods

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**Abstract**-In a previous study it was found that dynamic modulus (E) obtained from Impulse Load Test (ILT) is lower than dynamic modulus obtained from Ultrasonic Pulse Velocity Test (UPVT), which is theoretically not correct. In order to investigate this problem, the theoretical aspects involved in E-Calculations were checked by calculating the lateral strain involved in UPVT. Two finite element software programs (Marc and Patran) were selected for this purpose. In addition the effect of diameter on lateral strains of 12 inch length concrete samples was also investigated.

**Keywords**-Dynamic Modulus, Impulse Load Test, Ultrasonic Pulse Velocity Test, Finite Element Methods, Lateral Strains

## I. INTRODUCTION

Concrete is used in most civil engineering structures and therefore requires certain performance characteristics such as quality, workability and economy. Among them quality is most important and is measured by its strength, durability and dimensional stability. The strength of concrete is measured by Dynamic Modulus (E) Compressive Strength (Fc) etc. Among them Dynamic Modulus corresponds to a very small strain. This strength parameter is used in design for pavements and structures subjected to earthquake or impact loading. A large number of testing procedures are presently available for its determination. These procedures, used either in the field or the laboratory, are broadly classified in to destructive tests and non-destructive tests (NDT).

Destructive testing has been in use for a number of years. The structural evaluation of concrete can be made successfully with these tests. However, for existing structures, the tests are expensive and time consuming. On the other hand, NDT procedures are useful in that they are economical and provide a quick evaluation of concrete sample. Moreover, these testing procedures allow repeated testing of the same sample and make possible a study of the variation in properties with time. For Dynamic Modulus evaluation ILT and UPVT are available which in a previous study gave different results of the same sample.

These in-consistent results in Dynamic Modulus evaluation is theoretically not correct as the same phenomenon of wave travelling through a sample causing its vibration is involved in both these methods.

In UPVT wave velocity and ILT the natural frequency of the sample is used for dynamic modulus evaluation. Since the same wave is involved in both these methods, the dynamic modulus should be the same (ACI, 1976).

For the justification of these results, it is important to mention the detail of the solutions available for the dynamic modulus calculations in UPVT. Such solutions suggested by ACI (1945) and Long (1945) for the laboratory specimens, pavements, and mass concrete are given in Table I. Among them the one suggested for laboratory specimens was used to calculate the dynamic modulus [i]. In this solution it was assumed that in laboratory specimens, lateral expansion or contraction reduces the velocity of the longitudinal wave (ACI, 1976), which causes the wave to travel at a slight greater velocity. The situation represented by pavements is intermediate between those represented by laboratory specimens and the mass concrete (ACI, 1976) because the lateral displacements in pavements are suppressed in the direction of width but not in the direction of thickness.

The next step in this research was to check the extent to which the assumption of lateral expansion or contraction of laboratory specimens affects the wave velocity. For this purpose, two finite program were used to calculate the lateral strains in the 6×12-inch concrete samples tested by UPVT. Also the effect of diameter on the lateral strain of 12 samples was investigated in this study.

TABLE I  
SOLUTION FOR DYNAMIC MODULUS IN TIME TRAVEL METHOD [v], [vi]

Situation	Solution
Laboratory Specimen	$E = V^2 \cdot \rho$
Pavements	$E = V^2 \cdot \rho \cdot (1 - \mu^2)$
Mass Concrete	$E = V^2 \cdot \rho \cdot \frac{[(1 + \mu)(1 - 2 \cdot \mu)]}{(1 + \mu)}$

E = Dynamic Modulus of Elasticity

V = Pulse Velocity

$\rho$  = Density of the Concrete sample

$\mu$  = Poisson's Ratio of Concrete sample

The ultrasonic pulse velocity has been used on concrete for more than 60 years. Powers in 1938 and Obert in 1939 were the first to develop and extensively use the resonance frequency method [viii]. Since then, ultrasonic techniques have been used for the measurements of the various properties of concrete [ixxxviii]. Also, many international committees, specifications and standards adopted the ultrasonic pulse velocity methods for evaluation of concrete. Examples are the ASTM C597, BS 1881: Part 203 and ACI 224R, ACI 228.1R, ACI228.2R and ACI228.2R [xxvixxviii].

The variation of the results due to the surface properties, presence of steel reinforcement, presence of voids and cracks, properties of aggregate and mix proportions have been studied and shown in the literature [xii,xiv,xvi, xvii,xxviii]. Many attempts have been made to correlate the velocity to the strength of concrete either directly or by the use of combined ultrasonic and rebound hammer [xv, xxi, xxii, xxv, xxviii]. Special techniques for investigating damage in concrete by the use of wave velocity through cracked concrete have been introduced by Toutanji [viii], Selleck et al. [xxiii], Nogueira and Willam [xxiv].

From the literature review, it can be concluded that the ultrasonic pulse velocity results can be used to:

- a. Check the uniformity of concrete,
- b. Detect cracking and voids inside concrete,
- c. Control the quality of concrete and concrete products by comparing results to a similarly made concrete,
- d. Detect condition and deterioration of concrete,
- e. Detect the depth of a surface crack and
- f. Determine the strength if previous data is available.

## II. DETAILS OF ULTRASONIC PULSE VELOCITY TEST

The ultrasonic pulse velocity test is used for assessing the quality of concrete by measuring the longitudinal pulse velocity. The pulse is produced by an electro-acoustical transducer that is held in contact with one surface of the concrete sample being tested and received by a similar transducer in contact with the other surface. The equipment used in this (Model C-4901) was designed for both laboratory and field testing by James Instrument, Inc. the accuracy involved in this equipment is  $\pm 0.1$  microsecond. It generates low frequency ultrasonic pulses and measures the time taken for them to pass from one transducer to the other through the material interposed between them.

It gives a direct reading of the transmission time of an ultrasonic pulse passing from transmitting to a

receiving transducer. Two time ranges are incorporated covering from 0.1  $\mu$ sec. to 999.9  $\mu$ sec. (in units of 0.1 $\mu$ sec), and 1.0  $\mu$ sec. to 9999.0  $\mu$ sec. (in units of 1.0  $\mu$ sec.). an over range LED indicates when a range has been exceeded. The transmit time is displayed on a 4 digit, 0.5 inch Transflective Liquid Crystal. A nominal 0.5 to 8 microsecond variable delay control enables the instrument to be set to a reference reading with different types of transducers and cables. The control is used in conjunction with a standard reference bar, supplied with the instrument, and having a transmission time of 26  $\mu$ -sec. The exact time is being marked on the bar. If the transmitted pulse is not received, or when the transducers are removed from the test piece, the LCD display will automatically blink and the O/R indicator will flash once per second. This provides a warning if the instrument has inadvertently been left switched on. The instrument has been designed with site testing particularly in mind, to be fully portable, simple to operate and with a high degree accuracy and stability. Currently, there are at least three such instruments available commercially. In all these equipment the contact with the concrete is made with a suitable acoustic coupling medium, such as grease, petroleum jelly, etc.

There are three ways of measuring pulse velocity through concrete. One is the direct transmission method, in which the transducers are attached to opposite faces of the member; preferred wherever access to opposite sides of the component is possible because it provides a well-defined path length and results in maximum sensitivity. The same method was used to test the concrete samples placed in a container on sand. Later two transducers coated with vacuum grease were pressed on both faces of the concrete samples. When the reading on the time display unit was stabilized noted for calculating the dynamic modulus of the concrete samples.

## III. FINITE ELEMENT METHOD (FEM)

The purpose of using FEM in the study was to find the lateral deformations of 12 inch length concrete samples of different radii tested by UPVT. In this testing arrangement two types of loading conditions were applied. First a static loading condition was applied through the transducers by the operator. Secondly, a dynamic loading condition was applied due to pulses travelling from one transducer to the other. Two finite element software programs, Patran and Marc, were used for this purpose. The reason for using this software was the fact that, neither of the software was able to perform the analysis alone. As an example, Patran is not able to perform the dynamic analysis of a structure. On the other hand, Marc is not capable of reading the output or result files. It also cannot create the session files that represent the geometry, materials properties, and loading and boundary conditions of a

structure. For this reason, it was decided to use Patran for creating the session files. The type of the element used in the file was a hexahedron. A total of 1476 elements were created to represent the geometry of 12 inch length concrete samples of different radii. Some of the nodes at the center of the concrete sample were fixed in this file. The reason was that the software selected for the dynamic analysis was not able to handle the free-free boundary condition.

#### A. Details Software for FEM

The general applicability of the finite element method makes it a powerful and versatile tool for a wide range of problems. Hence, a number of computers program packages or software have been developed for the solution of a variety of structural and solid mechanics problems. Some of the programs have been developed in such a general manner that the same program can be used for the solution of problems belonging to different branches of engineering with little or no modification. Among these programs, only two were used for lateral deflection of concrete samples tested by UPVT.

Also lateral deflections in 12 inch length concrete samples of different radii were investigated in this research. Details of both of these software are given below:

##### 1) Patran

This finite element program has been designed to provide for easy and efficient utilization of human as well as computer resources. It has been implemented on a wide variety of computers, such as the Hewlett-Packard HP 90000. Patran is a solid modeler; a graphing imaging system; a modeler for finite element, boundary element, and finite difference analysis; an analysis tool; and a result evaluation system. As requirements change, Patran's flexibility provides an efficient mechanism to help the engineer meet the challenges of his work environment (Kart, 1985).

##### 2) Marc

Marc is a general purpose finite element program designed for the linear and non-linear analysis of structures in the static and dynamic regime. Its extensive element library makes it useful in elastic analysis and its broad coverage of the structural mechanics area makes it invaluable as a non-linear analysis tool. It is written in Fortran IV in general form with variable dimensions passed down to the subroutines. The user defines his own working space depending on element type, the size of the problem, and available memory (Kant, 1985).

## IV. LATERAL STRAIN EVALUATION

In this study lateral deflections of the concrete sample tested by UPVT (Fig.1 (a)) was obtained by

using FEM. These deflections were needed to check the validity of the assumptions used for the solution of a laboratory specimen.



Fig. 1. (a). Ultrasonic Concrete Tester

For this purpose, a concrete sample was made and tested by the ultrasonic pulse velocity test for its dynamic modulus evaluation. The value of dynamic modulus obtained in this testing was 6450967 psi, which was used for calculating the lateral deflection of the sample. At this stage, it is important to mention again that in ultrasonic pulse velocity test, two types of loading conditions are involved. First, a static loading condition which were applied by the operator through two transducers. Secondly, a dynamic loading condition, which was applied due to, pulses travelling from one transducer to the other.

The approximate value of the static loading was found by approximately applying the same amount of load by the operator on the weighing machine. Dividing this load by the area under the two transducers (Fig. 1(b)), a stress of 2.9 psi was obtained. This stress was applied by the operator through transducers on both faces of the concrete samples.

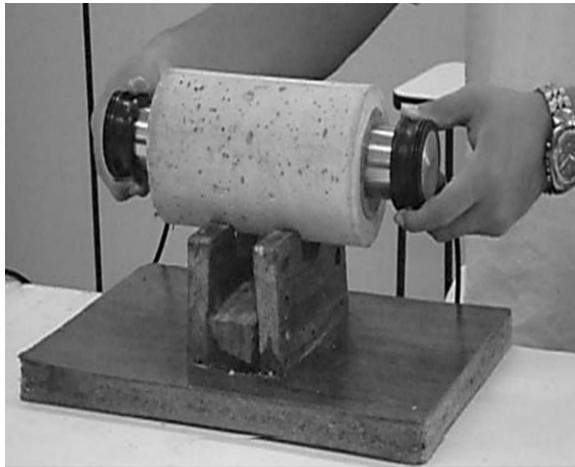


Fig. 1. (b). Sample Tested by Ultrasonic Concrete Tester

The loading conditions involved in the dynamic load are shown in Fig. 2. The loading condition indicates that a load of 0.01 pound is applied for a period of two micro-seconds with a frequency of ten cycles per second.

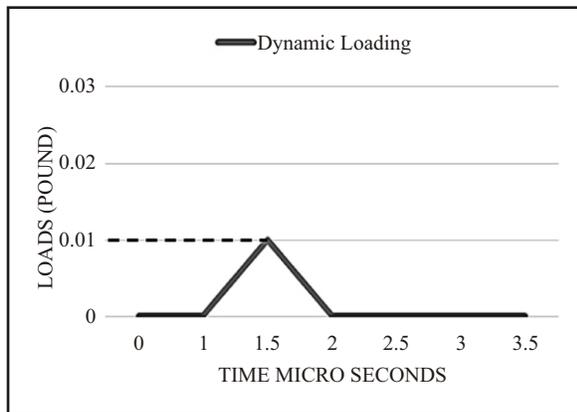


Fig. 2. Dynamic Loading (Ten Hz Per Second) involved in UPVT

After obtaining information about loading conditions, the next step was to analyze the lateral deflections with the help of FEM by using software Patran and Marc as mentioned earlier. Two programs were necessary because neither of the two was available to perform the analysis alone. Specifically, Patran is not able to perform the dynamic analysis of a structure. On the other hand, Marc is not capable of reading the output or the result files and cannot create the session file, which presents the geometry and properties of a structure. Moreover, it does not perform the analysis free-free conditions.

Considering all the limitations described above, it was decided to use Patran for creating session files, as well as to extract the results from the output files. The limitation of boundary conditions is Marc was

overcome by fixing some of the nodes at the center of the sample. These nodes were located on the face that had a radius of 0.985 inch and was perpendicular to the direction of wave propagation.

After making all the decisions about loading and boundary conditions, Patran. ses was created. Later, when the same session file was run by Patran, two other files, Patran. dat and Patran. out, were obtained. Using the 'Patmar' program a translation of Patran. out was made. Marc made it readable. Later with the help of a subroutine, named 'Kludge. For', the transformed files were run by Marc for finite element analysis. In the first run, all the loads were treated as if they were static in nature. For the dynamic analysis, a modification was made in the Marc. dat file. Listing of Patran. ses, and Marc. dat (modified) files is given in Annexure 1. Now, using the modified file, a second run was made, and several output files of the same type were obtained. Again, the file 'Marc. T16' was transformed back by the 'Marpat' program. As a result of which two output files, Patran.I0so.Dis, and Patron.I0so.Els were obtained. Both files are readable by Patran.

Patran.I0so.Dis files can be used to get the deformed shape of the sample. The values and contours for displacement in different directions can also be obtained from this file. Patran.I0so.Els can be used to get the values and contours for stresses in different directions. Patran.I0so.Dis with higher numbers can also be used to get the plot of deformed shape and the value of natural frequency of a sample in different modes of vibration. Patran.I0sl.Dis will give the plot and natural frequency in the first mode of vibration. Similarly, Patran I0s2. Dia will give the plot and natural frequency in the second mode of vibration and so on.

After obtaining the above results, the next step was to find the lateral deflections in the concrete sample. Fig. 3 shows the plots of contours and values of deflection in X- direction. Y=0, the deflection in the X-direction can be used for lateral or radial deflections. Since these deflections are changing in the Z-direction, it was decided to calculate the average lateral deflections in the concrete sample. Three locations, at the middle and at each end of the sample, were selected for this purpose. The locations of these deflections are also shown in Fig. 3. Once the three deflections were known, the average deflection and ultimately the average strain in the lateral direction was obtained. The value of this strain was  $2.2 \times 10^{-8}$  inch/inch, which is very small. Later the same type of analyses was made for 12 -inch length concrete samples of different radii Annexure 2. From these results the lateral strains at different radii were calculated. The plot of these lateral strains at different radii is given in Fig. 4. The following observations given in Table II can be made from this figure:

TABLE II  
EFFECT OF RADIUS ON LATERAL STRAIN

Diameter	Lateral Strain
(1) As diameter decreases	(1) Lateral Strain increases
(2) Below 4" diameter	(2) Lateral Strain increases dramatically
(3) Above 4" diameter	(3) Change in Lateral Strain is relatively small.

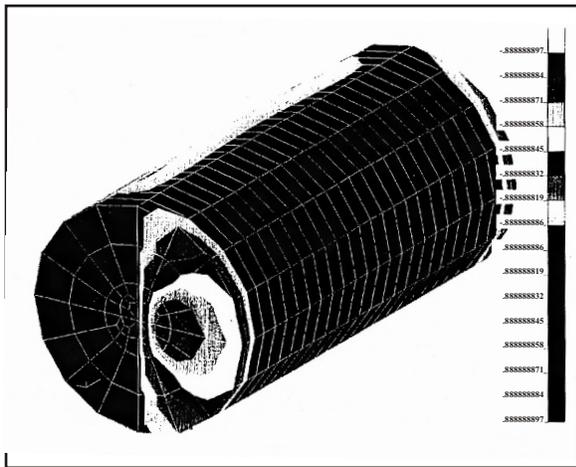


Fig. 3. Deflections (X-Direction of Concrete Samples tested by UPTV by Using Finite Element Methods

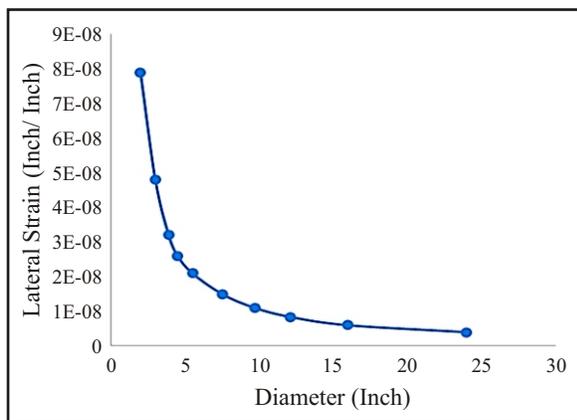


Fig. 4. Effect of Diameter on Lateral Strain of 12 Inch Long Concrete Sample

### V. CONCLUSION

The results obtained from FEM show that lateral strain in 6x12 inch concrete samples due to UPVT are so small that cannot affect the wave velocity as reported by Shah 1970. Under these circumstances for 6x12

inch laboratory specimens the ACI suggested solution is not appropriate. Hence 6x12 inch concrete samples should be treated as mass concrete which require poisons' ratio of concrete for its Dynamic Modulus evaluation as given in Table I.

```

HEX/8/0      .
N            5
2           3
2           1
4           P
12          WI
ME          4
H14         PL
HEX/8/0     11
N           7
2           4
2           PF, H1T #, HEX/8/0, 1
4           END
12          6
ME          3
H15         1
HEX/8/0     2
N           7
2           5
2           1
4           1
12          1
ME          CONCRETE CYLINDER UNDER ULTRASONIC TESTING
H16         N
HEX/8/0     10
N           6
2           2
2           2
4           4
12          12
FEG         2
N           2
N           1
N           1
PMAT, 1, ISO, 6. 55E6, , . 22, 2. 2803E-4
DF          DF, H13T16,PRESS, // -2. 9, 1, FA6
DF, H5T8, PRESS, // 2.9,1,,FA5
DF, H5T8, FORC, // .01,1,,FA5
DF, H13T16, DIS, 0/0/0, 2, FA5
DF, H5T8, DIS, 0/0/0, 2, FA6
END
    
```

Fig. 5. Listing of Patran.ses File (Continued).

**Annexure 1**  
Using of Patran.ses and Marc.dat (Modified Files)

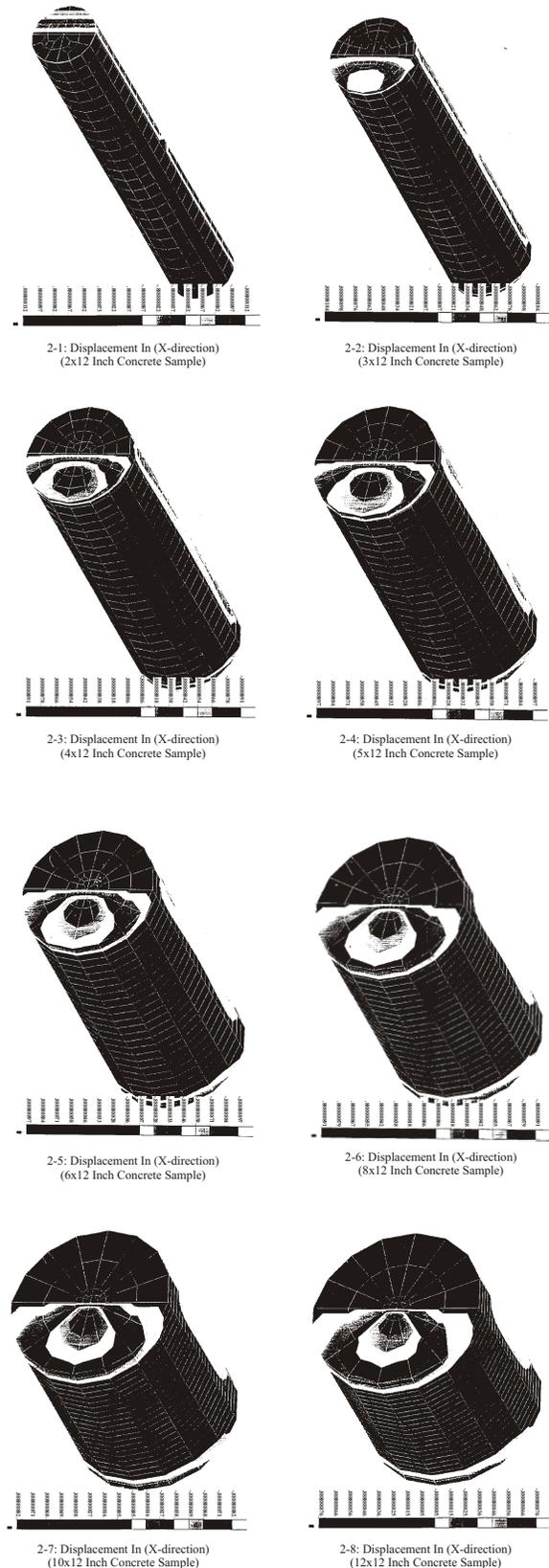
GO	ME	HEX/8/0	HEX/8/0	
1	H3	N	N	
1	HEX/8/0	2		2
1	N	2		2
GR, #, , O	2	4		4
LI, 4#, ARC, . 985/0/0/				
.985/0/ 985/360, 1	4	12		12
GR, #, TR, -2, 065, 1	2	ME	ME	
LI, 4#, ARC, . 985/0/0/				
.985/0/ 985/360, 5	4	H9	H9	
PA, 4#, 2L, , 1/2/3/4,				
5/6/7/8	12	HEX/8/0	HEX/8/0	
GR, #, TR, . 985, 1	ME	N	N	
LI, 2#, ST, , 1/9, 9/3	H4	2		2
PA, 4#, 2L, , 1/2/3/4,				
9/10/10/9	HEX/8/0	4		4
VI	N	2		2
1	2	4	4	
23, -34	4	12		12
PL	2	ME	ME	
VI	4	H10	H10	
2	12	HEX/8/0	HEX/8/0	
O, -180	ME	N	N	
PL	H5	2		2
PA, 8#, TR, //6.02,				
1T8	HEX/8/0	4		4
HP, 8#, 2P, , 1 T8,				
9T16	N	2		2
HP, 8#, TR, // 6. 02, 1				
T8	2	4		4
SET, LABEL, OFF	2	12		12
PL	4	ME	ME	
END	12	H11	H11	
ME	ME	HEX/8/0	HEX/8/0	
H1	H6	N	N	
HEX/8/0	HEX/8/0	2		2
N	N	4		4
2	2	2	2	
4	2	4	4	
2	4	12		12
4	12	ME	ME	
12	ME	H12	H12	
ME	H7	HEX/8/0	HEX/8/0	
H2	HEX/8/0	N	N	
HEX/8/0	N	2		2
N	2	4	2	4
2	2	2	2	
4	4	4	4	
2	12	12	12	
4	ME	ME	ME	
12	H8	H13	H13	

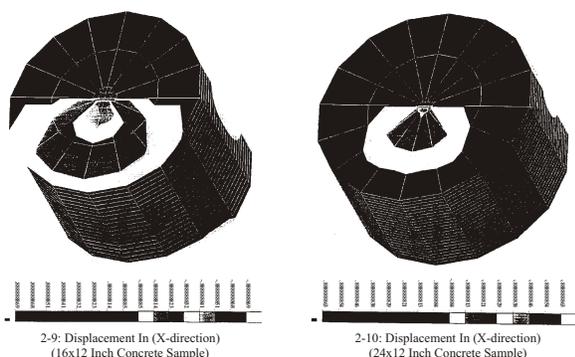
Fig. 6. Listing of Patran.ses File

DYNAMIC	1	3	1	
END				
END OPTION				
MODAL SHAPE				
40,				
CONTINUE				
RECOVER				
	2			
CONTINUE				
DYNAMIC CHANGE		0.00001	2	1
0.00001				1
FORC				
2, 0.01,				
H5T8, FA5				
CONTINUE				
DYNAMIC CHANGE		0.00001	2	1
0.00001				1
FORC				
2, -0.01,				
H5T8, FA5				
CONTINUE				
DYNAMIC CHANGE		0.001		
0.00002			49	3
				49
TRACTIONS	1			
2	2			
1	2			
CONTINUE				

Fig. 7. listing of Marc.dat file

Annexure 2  
Test Results Obtained from Finite Element Analysis of  
12 inch Length Concrete Samples of Different Radii





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